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J. G. Daunt and Bernard Kaplan

September 30, 1952

THE OHIO STATE UNIVERSITY
RESEARCH FOUNDATION

Technical Report No. 1
RF Project 453

R E P O R T

by

THE OHIO STATE UNIVERSITY
RESEARCH FOUNDATION

Columbus 10, Ohio

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OFFICE OF NAVAL RESEARCH
Contract N6onr22527

Investigation of: DETECTORS FOR MILLIMETER RADIATION

Subject of Report: Technical Report

Submitted by: J.G. Daunt and Bernard Kaplan

Date: September 30, 1952

CONTENTS.

LOW TEMPERATURE DETECTORS FOR MILLIMETER RADIATION

1. Summary of scope and purpose of project.

The purpose of the investigations undertaken under this project is the study of some fundamental physical problems associated with thermal detection of radiation. It is well known that for the detection of coherent radiation in the radio and microwave regions "mixer" detectors, using a local source of radiation of nearly the same frequency as the incident signal, have the smallest minimum detectable power values for signal equal to noise. On the other hand recent extensions of investigations to higher and higher radiation frequencies in the millimeter wavelength or in the far infra-red region may result in some valid requirements for thermal detectors. To assess fully the value of such detecting systems it is considered that further work is necessary. Such work can be subdivided into theoretical and experimental approaches and it is the purpose of this project to carry out such investigations.

Theoretically it is possible to calculate approximately the minimum detectable power for signal equal to noise for a thermal detector and it is found in general that this minimum detectable power is diminished when the temperature is reduced and when the temperature dependency of the observed physical parameter is increased. In consequence one experimental study being carried out under this project is a fundamental study of the possibility of the development of phosphor-bronze and partially superconducting metallic bolometers at very low temperatures, which would appear to offer many advantages. This study comprises the major scope of the work under this project.

2. Experimental Work (Outline).

12 experimental runs at the temperature of liquid helium ($1^{o}K$ to $4.2^{o}K$) have been carried out, with a total time at these temperatures of about 100 hours. The experiments concerned (a) current noise measurements at low temperatures in partially superconducting metals and (b) observations with prototype bolometers. Details of these two groups of experiments are given below in sections 4 and 5.

3. Current Noise in Partially Superconducting Resistors at Temperatures down to 2°K.

(a) Abstract.

Measurements have been made of the current noise power in tantalum and leaded phosphor-bronze in the helium temperature region, the noise power being obtained as a function of the frequency of observation from 200 to 4000 cycles/second. No current noise was observed in tantalum in the normal or in the superconducting state at 4.2°K. In the intermediate state, however, when the tantalum specimen was maintained partially superconducting in a magnetic field at 4.2°K, large current noise power was observed which was found to be proportional to the square of the d-c biasing current, i^2. The ratio, $(n - 1)$, of the current noise power to the Johnson noise power in Ta in the intermediate state was found to be $(n - 1)/i^2 = 15\ (\text{ma})^{-2}$. A tentative explanation has been put forward on the basis of temperature fluctuations in the specimen.

No current noise was observed in the partially superconducting leaded phosphor-bronze specimen, although its resistivity was a marked function of the temperature in the temperature range of observation (2°K to 4°K).

(b) Introduction.

In this section a report is given of experiments performed to measure the current noise in partially superconducting resistors at very low temperatures. The current noise is the excess electrical voltage fluctuations, over and above the thermal fluctuations known as "Johnson noise", produced when a steady d-c biasing current is passed through the resistor. Measurements of current noise as a function of frequency of observation reveal much information regardind relaxation effects among the current carriers in electrical conductors. It was thought of interest, therefore, to make measurements of current noise on superconductors in their intermediate state, a region where the resistivity of the superconducting element is neither completely zero nor completely normal. These experiments therefore involved noise measurements on specimens at liquid helium temperatures.

Two different specimens were employed, namely, pure tantalum and leaded phosphor-bronze, both of which can be maintained in a partially superconducting state. The results obtained for the two specimens were widely different, as is reported below.

A possible explanation of the results as being due to temperature fluctuations in the specimens is put forward in sub-section 4 (f).

(c) Experimental Arrangements

A schematic diagram of the apparatus used to measure the electrical noise in resistors at low temperatures is given in Fig. 1, and a picture of the general arrangements is given in Fig. 6. The specimen of interest was located inside a low temperature cryostat, within suitable shielding, and it could be immersed directly in liquid nitrogen, liquid hyrogen or liquid helium within the cryostat Dewar. Small currents, up to about 20 ma, could be passed through the specimen, the current being supplied by a biasing unit consisting of a 1.5-volt battery, a decade resistor and a milliammeter maintained at room temperature. The a-c component of the potential across the specimen was led, via the potential leads, to an input transformer. In order to avoid d-c current through this transformer, a condenser blocking unit was inserted in the potential leads, the condenser being of 2000μf capacity. Measurements were made over the audiofrequency range to 5000 cps.

The input transformer was U.T.C. type LS-14X having a measured impedance matching ratio of 2×10^4 :1 for a 10 ohm input resistance over the range of audiofrequencies used in the experiments. This transformer was located in liquid nitrogen in order to reduce its temperature and so reduce its electrical noise. The observed equivalent noise resistance (normalized to room temperature) at 500 cps was 24 kilo-ohms with primary shorted. The secondary of the transformer led into a specially constructed low noise preamplifier. The observed equivalent noise resistance of this amplifier over a narrow band centered at, for example, 500 cps, was 2000 ohms. This first tube of the preamplifier was a selected 6AC7, operated as a pentode with heater voltage set at 4 volts and 0.8 ma, anode current; and the circuit was arranged to give a broad-band response in the audio frequency range with a high-frequency cutoff at 10,000 cps. The second, narrow-band, amplifier was a General Radio sound analyzer, type 760-A, using a twin-T feedback network giving a narrow bandwidth at a frequency which could be varied over the audiofrequency range. At 500 cps, for example, the measured bandwidth to half-power was $\Delta f = 5$ cps. The power amplifier and detector fed a d-c recording microammeter. The detector was a EMBY selenium rectifier, type B S, which was found to give a square-law response over the range of powers and frequencies used.

Two methods of checking the gain and noise factors of the amplifiers and the input transformer at various frequencies were adopted. First a calibrated signal could be fed from an audiofrequency signal generator and a calibrated attenuator directly to the grid of the preamplifier. Secondly, the Johnson noise voltages generated across known resistors at room temperature could

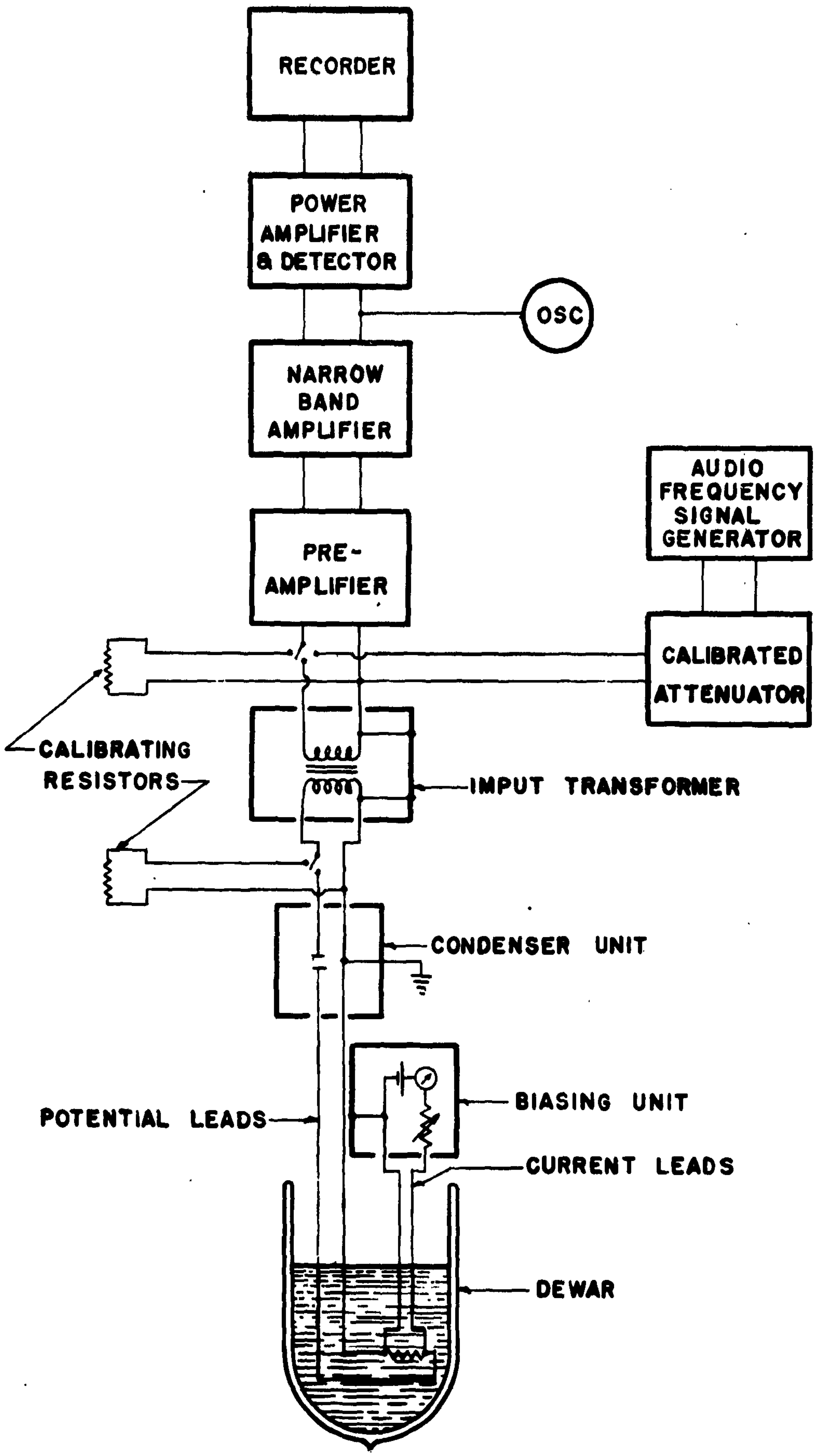

FIGURE 1. Block diagram of apparatus

be applied as diagramatically indicated in Fig.1, either to the grid of the preamplifier or to the primary of the input transformer.

Considerable care had to be taken in the method of grounding the various units and in shielding the connecting leads, features which could not be included in the very simplified diagram of Fig. 1.

As an illustration of the performance of the equipment, Fig. 2 shows a record from the recorder taken at 500 cps. Region (A) represents the output when a 10-ohm resistor at room temperature was placed across the transformer primary. This then gives a measure of the Johnson noise across 10 ohms at 300°K, which, for the bandwidth of $\Delta f = 5$ cps, would correspond to an rms voltage of 9.1×10^{-10} volts. Region (B) represents the output due to a 10-ohm resistor at 77°K, corresponding to an rms voltage of 4.6×10^{-10} volts. Region (C) represents the output when the primary of the input transformer was shorted. From Fig. 2 it will be seen that the minimum detectable signal for signal equal to the noise of region (C) would approximately correspond to the Johnson noise across 10 ohms at about 10°K, i.e. 1.5×10^{-10} volts rms.

(d) Specimens Employed

Two different specimens were employed, the first being a resistor of tantalum, which is well known to become superconductive at 4.38°K [1] and the second of leaded phosphor-bronze which was first shown by Keesom and Van den Ende [2] to have an anomalously high temperature coefficient of resistance in the liquid helium region.

I. Tantalum. The tantalum specimen, supplied by Fansteel Metalurgical Corp., was a coil of 0.007 inch diameter wire 500 inches long, of high purity, the coil being wound in a bifilar, non-inductive manner on a 0.264 inch diameter form. The room-temperature resistance of the coil was 80.2 ohms, and at 4.2°K in the normal state (with a d-c magnetic field of 150 gauss externally applied, which was greater than the threshold field) its normal resistance was 5.18 ohms. The measured isothermal transition at 4.2°K from the

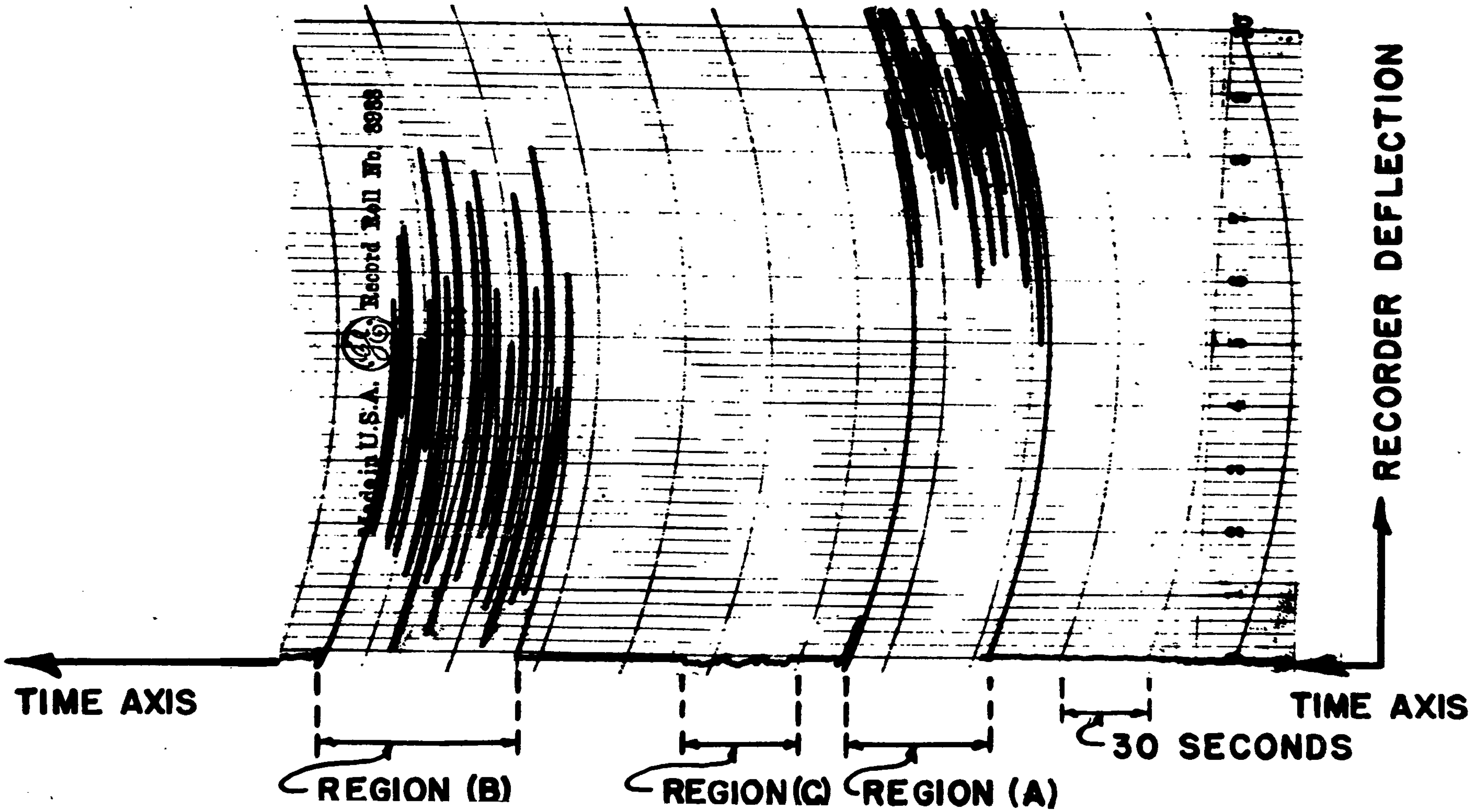

FIGURE 2. Record taken at 500 cps. Region (A), output for 10 ohms at room temperature at input. Region (B), output for 10 ohms at 77°K at input, Region (C), output for zero ohms at input (short).

superconductive state to the normal state in an applied transverse magnetic field is shown in Fig. 3, which plots the d-c resistivity of the specimen versus the applied transverse magnetic field. It will be seen that the transition is spread over a range of magnetic field values, which is not so wide, however, as is to be expected for transversely applied fields. In this transition, the specimen is in the so-called intermediate state. The observed value of the magnetic threshold field, 76 gauss, at which all trace of superconducting intermediate state has disappeared at 4.2°K is in good agreement with the threshold field results previously observed by one of us using a magnetic method.[3]

II. Leaded phosphor-bronze. The phosphor-bronze wire, of diameter 0.002 inch, kindly placed at our disposal by Dr. M.C. Desirant, contained a small percentage of Pb impurity. The specimen was wound from 120 inches of wire in a bifilar manner on a mica strip of rectangular cross-section 0.186 x 0.066 inch. The resistance of the wire at 300°K was 5.76 ohms; at 4.2°K it was 3.14 ohms; and at intermediate temperatures the resistance was found to be a linear function of temperature. Thus, there was not a great variation of resistivity over this range of temperature. Below 4.2°K, however, the resistivity showed a marked temperature dependence as is illustrated in Fig. 4, which shows the measured resistance versus temperature. At 2.2°K, for example, the temperature coefficient of resistivity, α, is 0.15 per degree K. The large value of α makes this wire of great value for resistance thermometers in the helium temperature region.[4] The Pb impurity does not go into solid solution in the phosphor-bronze, and presumably the variation of resistivity with temperature is due to filamentous unconnected regions of pure Pb phase, created in the wire by the drawing process, becoming superconductive or partially superconductive over a range of transition temperatures.

(e) The Measurements

Fig. 5 gives the results of measurement of current noise on the tantalum at a frequency of 500 cps with $\Delta f = 5$ cps. The left hand ordinates plot the average value of the recorder reading obtained by averaging the records, of the type illustrated in Fig. 2, over a long period of time. The right hand ordinates plot the square of voltage, v_g^2, which applied to the grid of the preamplifier, produces an equivalent recorder reading. The v_g^2

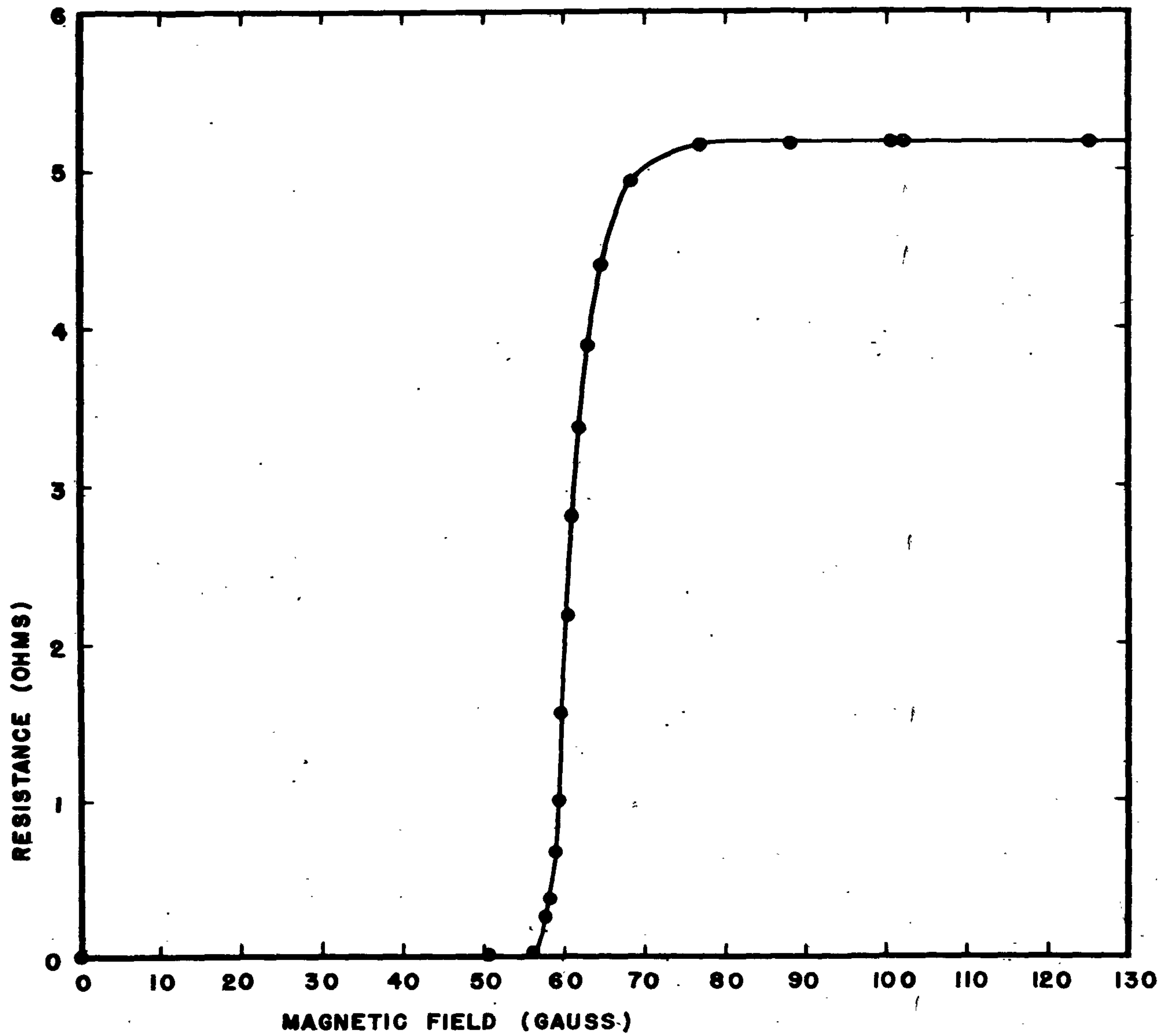

FIGURE 3. Resistance of tantalum specimen at 4.2°K as a function of the applied d-c magnetic field.

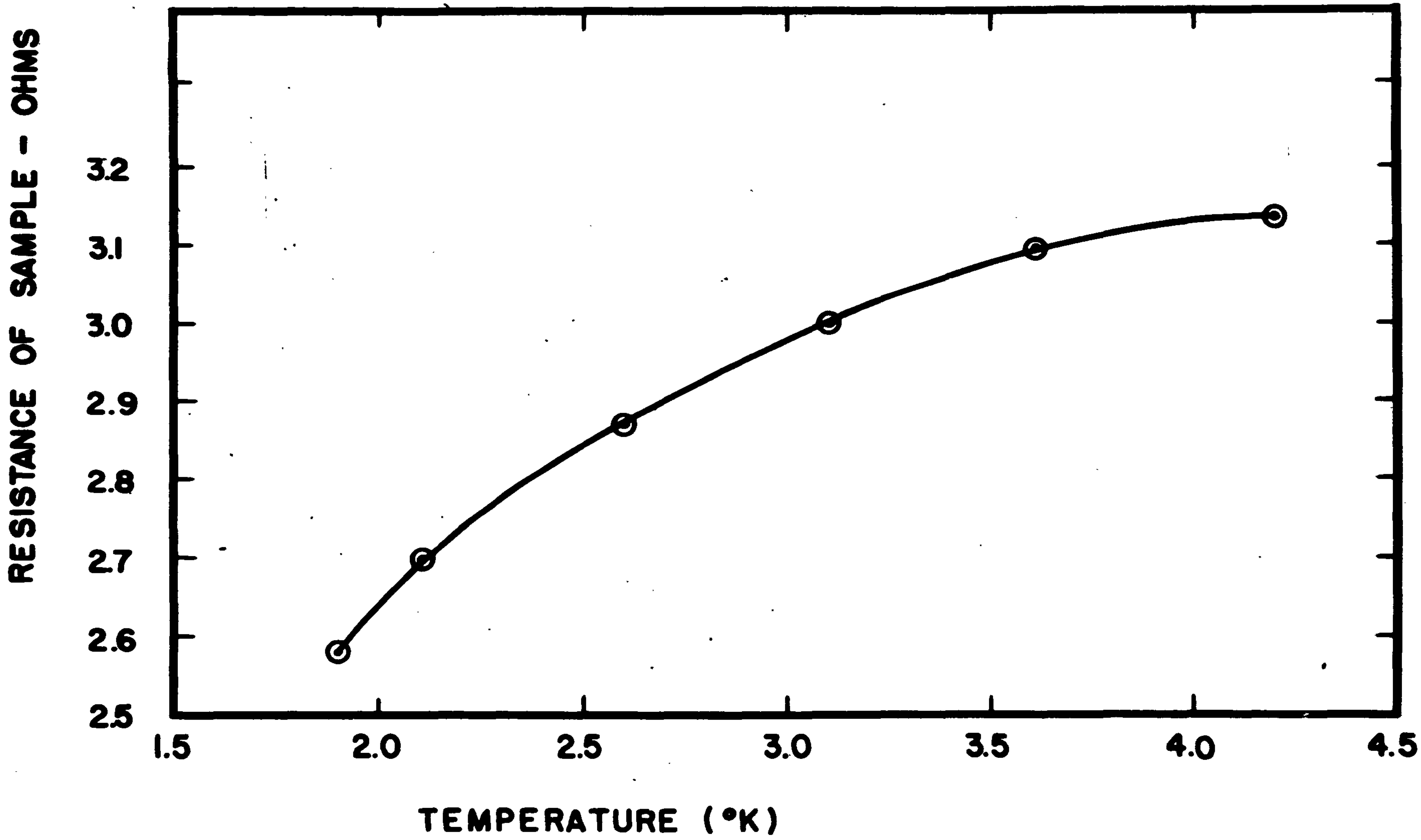

FIGURE 4. Resistance of leaded phosphor-bronze wire as a function of temperature.

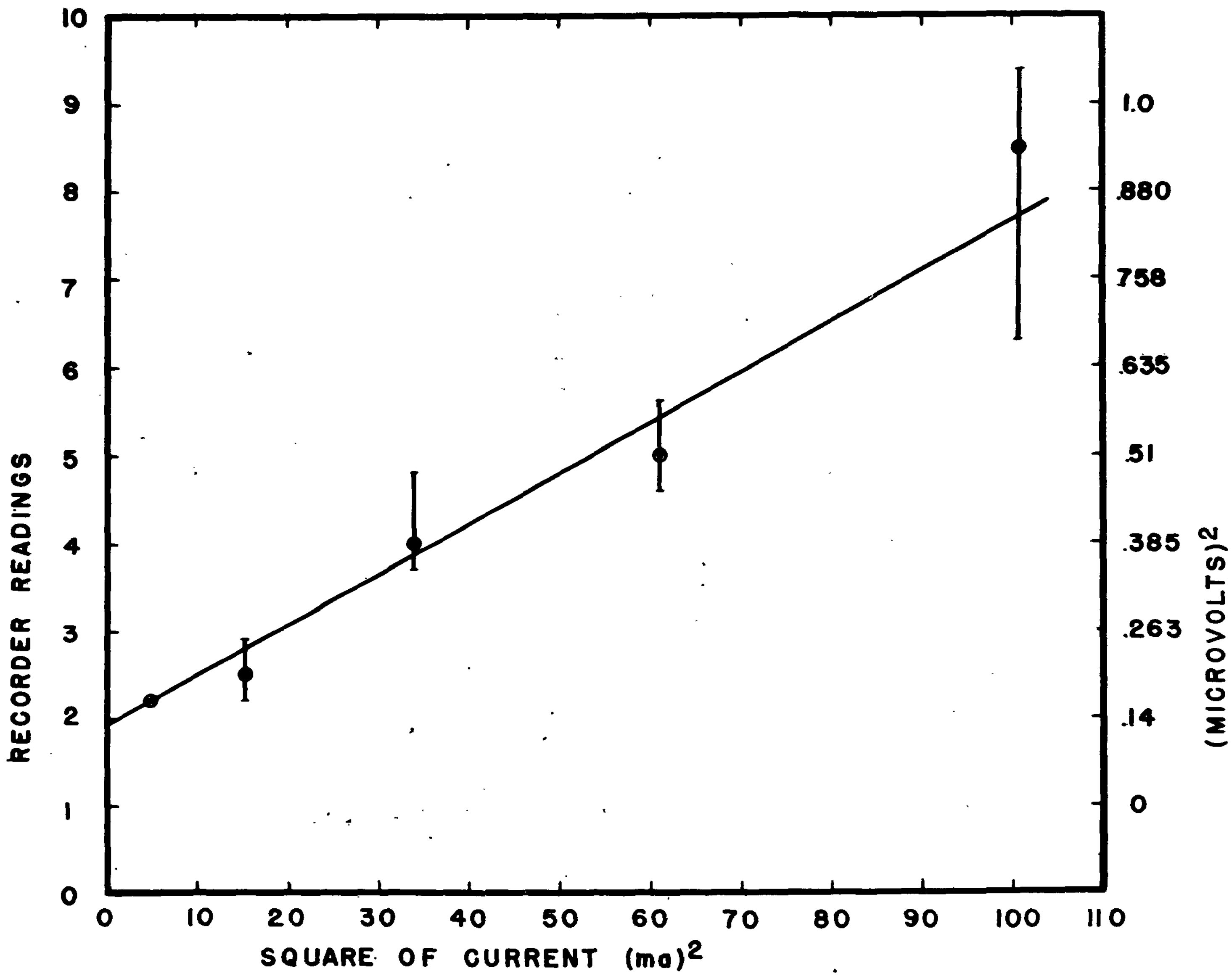

FIGURE 5. Noise output from tantalum specimen in the intermediate state as a function of the square of the biasing current.

calibration was obtained by employing the signal generator and attenuator. The signal generator had to be employed owing to the large values of current noise encountered in the tantalum specimen in the intermediate state. It should be noted here that for smaller v_g^2, the calibration was usually done by using the Johnson noise across known unbiased resistors at room temperature. The abscissae of Fig. 5 plot the square of the biasing current (in milliamperes squared) that was passed through the specimen.

The curve of Fig. 5, obtained from measurements of tantalum at 4.2°K in a magnetic field of 64.3 gauss, shows that the noise power increases proportionally to the square of the biasing current, i^2, and that the effect is large.

For tantalum in the completely superconducting state at 4.2°K or in the completely normal state at 4.2°K in a magnetic field of 99.5 gauss, our observations showed no measurable increase in noise output when biasing currents up to 10 ma were sent through the specimen.

Curves similar to that of Fig. 5 were measured at a number of spot frequencies and all the results were of the same character, indicating considerable "current noise" due to the biasing currents in the intermediate state. No current noise was observed, however, in the normal state at any temperature up to and including room temperature.

In order to present the accumlated data conviently we have evaluated a parameter, n, given by

$$n = \frac{\text{total noise power in resistor}}{\text{Johnson noise power in resistor}} = \frac{\text{current noise power}}{\text{Johnson noise power}} + 1 \qquad (1)$$

The evaluation of n, or rather (n-1), has been made from the equation

$$(n-1) = v_g^2/4KT_sR_s\Delta f\,\Gamma \qquad (2)$$
$$= \beta i^2$$

where R_s and T_s are the resistance and temperature of the specimen, v_g^2 the square of the voltage at the grid of the pre-amplifier corresponding to the recorder reading of Θ at a current of i, and where Γ is the effective impedance ratio of the input transformer. Since v_g^2 was found to be proportional to i^2, we have $(n-1) = \beta i^2$ where β was found to be frequency dependent.

In Table 1 the results are presented of the evaluation of β, i.e. of $(n-1)/i^2$ in $(\text{milliamperes})^{-2}$. Also, values of (n-1) expressed in decibels (db) for i = 10 ma are given in Table 1. The accuracy of the observation of (n-1) at 10 ma was probably not better than ± 4 db at frequencies above 500 cps. Below this frequency the accuracy was poorer.

As will be seen in Table 1, within the limits of error the values of (n-1) for a given biasing current were approximately independent of frequency in the range 750 to 4000 cps. At 500 cps and below the values of (n-1) are larger. Whether this is a true effect or may have been due to spurious pickup noises during the experiments is not yet clear. Further experiments are being planned to test this point in detail.

Measurements on the phosphor-bronze at 4.2°K and at 2.2°K indicated no observable current noise for biasing currents up to 10 ma over the range of frequency 100 to 5000 cps. The accuracy of the experiments allowed the conclusion to be made that even at the highest biasing current employed, namely 10 ma, the maximum value of the ratio of the current noise power in the resistor to the Johnson noise power, i.e. of (n-1), was 4.7 db.; and that in all probability (n-1) is zero.

(f) Interpretation of the Results

I. Normal State. The possibility of the occurrence of current noise in normal metals has been discussed by Brillouin [5]. He supposed that the total number of electrons suffered random fluctuations, the lattice acting as a reservoir which can give out and receive the variation in the number of electrons. He showed for a degenerate or partially degenerate system that the integrated current fluctuations, $\overline{\Delta J^2}$, are given by :

$$\frac{\overline{\Delta J^2}}{J^2} = \frac{\overline{\Delta N^2}}{N^2} = \frac{1}{N}\left\{ \frac{3mkT}{h^2}\left(\frac{8\pi D}{3n}\right)^{2/3}\right\} \qquad (3)$$

where n is the number of electrons per cc and where Δ is a correction term to allow for interelectronic interaction, given by

$$\Delta^2 = 1 + \frac{Ne^2}{m\ell^2}\,L,$$

TABLE 1

f (cps)	$(n-1)/i^2$ $(ma)^{-2}$	(n-1) for i = 10 ma (db)
250	900	49.5 ± 5
500	102	40 ± 5
750	40.5	36 ± 4
1000	27	34.3 ± 4
1500	20	33 ± 4
2000	4.8	27 ± 4
2500	15	32 ± 4
3000	4.6	27 ± 4
4000	15	32 ± 4

in which ℓ is the length of the wire and L its self-inductance. For no interaction between the electrons, i.e. no self-induction, $\Delta = 1$.

This formulation leads, under the conditions for the specimens used in our experiments, to the approximate inequality:

$$\frac{\overline{\Delta J^2}}{J^2} < 10^{-24}$$

which would yield an rms fluctuational voltage, at a biasing current J = 10 ma of less than about 10^{-13} volts. This value, which is the integrated value over all frequencies, lies well below our observational limits. The observed absence of current noise in our experiments on the metals in the normal state therefore is to be expected on the basis of Brillouin's theory. Only if the volume of the metallic specimens were to be made very much smaller would current noise be expected to be observable, since only for very small volumes will the degeneracy of the electron gas system be removed. The attempts that have been made to observe such current noise in metallic films of small volume by Bernamont [6] and Surdin [7] have not led to unambigous results.

II. Intermediate State. The very large current noise observed in tantalum in the intermediate state is of interest. Large current noise has previously been reported by Andrews [8] for NbN in the transitional region between superconducting and normal states in the absence of a magnetic field, but at that time it was not clear whether the effect might not have been partly due to the astoichiometric and semimetallic characteristics of the NbN. Our results, however, indicate that even for a pure metal such as tantalum, large current noise is to be associated with the intermediate state and that in the normal or completely superconducting states the current noise is negligible.

Two possible explanations of the effect present themselves: (1) the current noise may be due to temperature fluctuations of the specimen as a whole, which, having a large value of (dR/dT) in the intermediate state, would therefore show current fluctuations; or (2) the current fluctuations may be due to relaxation effects of the electrons or groups of electrons, as yet unspecified, which are characteristic of the intermediate state.

The conditions necessary for the observation of fluctuations of type (1) have been considered independently by Milatz and Van der Velden [9] and by Daunt [10] and Kompfner [11] and it can be shown that the mean square fluctuationalvoltage, $\overline{\Delta V^2}$, observable on passing a biasing current i through the specimen would be given by :

$$\overline{\Delta V^2} = i^2\left(\frac{dR}{dT}\right)^2 \overline{\Delta T^2} = i^2\left(\frac{dR}{dT}\right)^2 4kT^2 \frac{G}{G^2 + \omega^2 C^2} \Delta f \tag{4}$$

where (dR/dT) is the slope of the resistance vs. temperature curve, G and C the thermal conductance to the surroundings and the heat capacity of the specimen, ω the angular frequency of noise observation and Δf the band width of observation. The value of the ratio $(n - 1)$ of the current noise to the Johnson noise in the specimen is therefore given by:

$$(n - 1) = (Ri^2)\,\alpha^2 T\left(G/G^2 + \omega^2 C^2\right) \tag{5}$$

where (Ri^2) is the power dissipated in the specimen and α its temperature coefficient of resistance.

For our tantalum specimen

$$\alpha = \frac{1}{R}\frac{dR}{dT} = \frac{1}{R}\frac{dR}{dH}\left(\frac{dH_c}{dT}\right)$$

where dH_c/dT is the slope of the magnetic threshold curve at the temperature of the measurement. Using the value of dH_c/dT of -325 gauss/degree obtained previously by one of us [3] and putting $R = 3$ ohms and $dR/dH = 0.73$ ohms/gauss (obtained from Fig. 3 at 61 gauss), we obtain $\alpha = -79.0$ (deg K)$^{-1}$. If it is supposed that in the frequency range of measurement $G > \omega C$, then we get from equation (5):

$$\frac{(n-1)}{i^2} = 7.8 \times 10^{-2}/G \text{ (ma)}^{-2} \qquad (6)$$

provided G is measured in watts/deg.

The results given in Table 1 for the observed values of $(n-1)/i^2$ could be accounted for by temperature fluctations, therefore, as in equation (6), provided the value of the thermal conductance G of the specimen to its surroundings is of the order of magnitude 5×10^{-3} watts/deg. Since the specimen was directly immersed in liquid helium at 4.2°K, values of G as high or higher than this are possible. Until G is directly measured in subsequent experiments, the possibility cannot be excluded that the observed current noise in tantalum in the intermediate state is due to temperature fluctations.

Temperature fluctations in the phosphor-bronze specimen would not be expected to be observable, since for the phosphor-bronze at 2.2°K, $\alpha = 0.15$ deg^{-1}, giving

$$\left[(n-1)/i^2\right]_{\text{Ph-Br.}} \leq 2.7 \times 10^{-7}/G \text{ (milliamps)}^{-2} \qquad (7)$$

Since it is likely, from the similar experimental arrangements, that $G_{\text{Ph-Br}} \approx G_{\text{Ta.}}$, this value of $(n-1)/i^2$ would be unobservable in our experiments.

Before it can be definitely established whether the observed current noise in tantalum is due, as seems likely, to temperature

fluctations of the specimen, it would be inappropriate to consider in detail the second possible mechanism of current noise, namely electronic relaxations effects in the conductor.

(g) Future of Tantalum as a bolometer element.

For the absorbed signal power, W, to be equal to the noise power, Daunt [10] has shown that

$$W^2 = 4KT^2 G \Delta f \left\{ 1 + \frac{G^2 + \omega^2 C^2}{G P \alpha^2 T} \right\} \tag{8}$$

in which the contribution to the noise power due to temperature fluctuations is revealed by the first term on the right hand side, and in which the contribution due to Johnson noise is given through the second term. It will be seen from (8) that as $\alpha \to \infty$, the value of W tends to an ultimate minimum given by temperature fluctuations alone. It is concluded, therefore, that if, for any fixed values of G, C and ω, the value of α is sufficiently large to allow the observation of temperature fluctuations, then W reaches values close to its ultimate minimum. If, therefore, the current noise observed in the tantalum specimen in the intermediate state is in fact due to temperature fluctuations, then this specimen should form a material especially suitable for bolometers and should give very low W values for signal equal to noise.

4. Experimental Tests of a Prototype Bolometer of leaded Phosphor-Bronze in the partially Superconducting State.

(a) Introduction.

In order to establish quantitative data regarding the design and possible performance of bolometers using partially superconducting elements, it was decided to carry out preliminary measurements on a bolometer using leaded phosphor-bronze as the bolometric material. No attempt was made to optimize the parameters involved in the construction, it being thought worthwhile at first to get preliminary data wherefrom optimizing calculations could be performed. As will be seen from the following sub-sections, the data we obtained was encouraging and led us to the possibility of design of a more sensitive instrument.

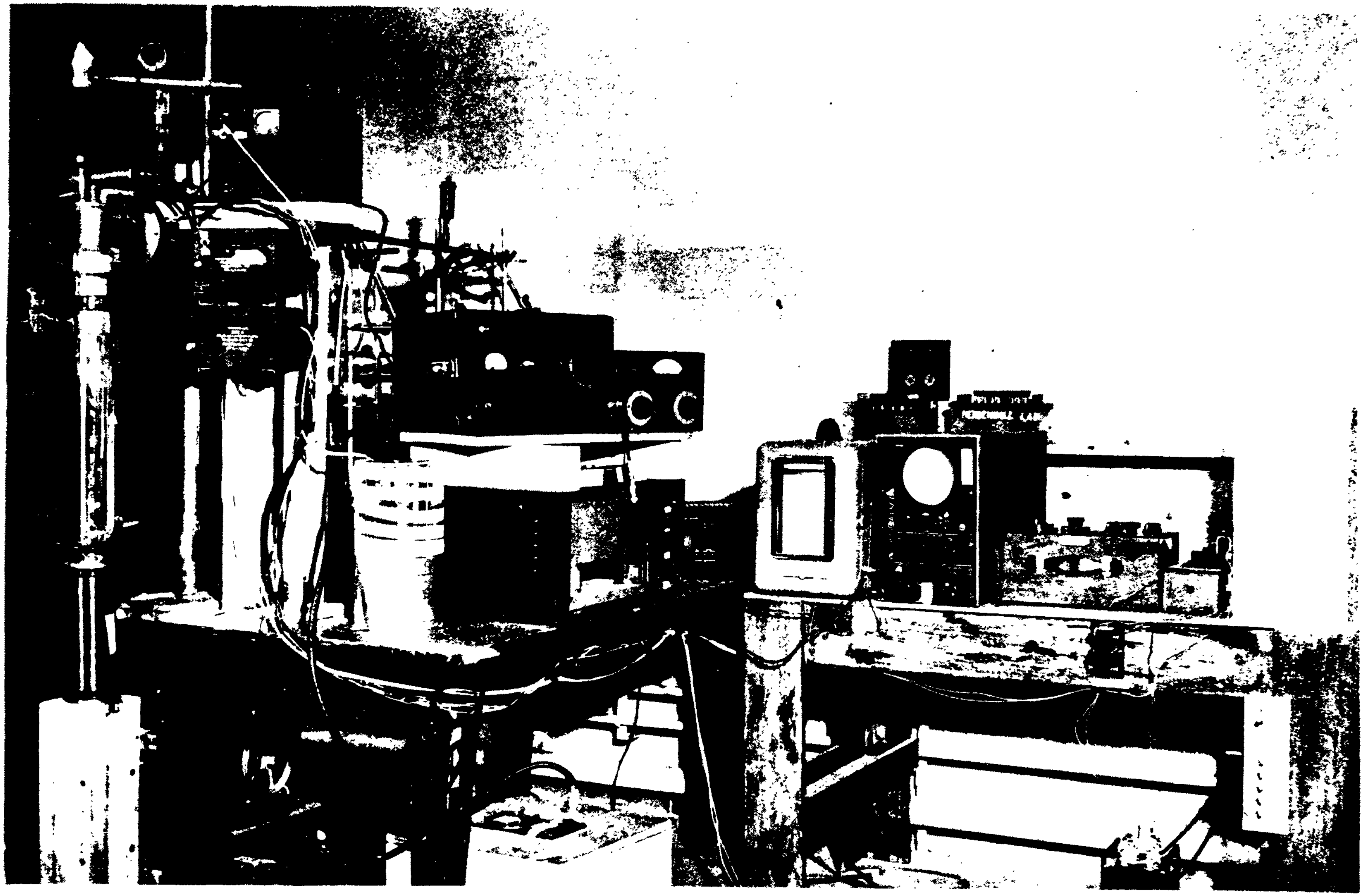

FIGURE 6 - The equipment for noise measurements, showing the magnet coil around the cryostat for maintaining the tantulum specimen in the intermediate state.

(b) The experimental arrangements.

A schematic diagram of the bolometer is given in Fig. 7. It consisted of a copper cylinder and cone, of over-all length 3.49 cm, of orifice diameter 0.66 cm and of wall thickness 0.025 cm, which served as the absorber of radiation. By suitable blackening of the interior of the cylinder and cone, e.g. by adhesive quartz powder, the unit would act almost as a blackbody and be suitable for absorption of radiation from the infrared into the millimeter wave region. The copper had a total surface area of 10.4 cm^2 and a mass of 1.31 g.

On the outer surface of the copper cylinder and cone assembly was wound 71 cm of leaded phosphor-bronze wire, insulated from the copper by a layer of varnish and lens paper. The wire was 0.005 cm in diameter and was of the same stock as that used for the experiments reported in Section 3 above, and it was wound in a non-inductive manner. The phosphor-bronze wire had current and potential leads attached to it and constituted the bolometer element. It was mounted, as is shown diagramatically in Fig. 8, in a space containing helium vapor at a temperature which could be maintained constant at any value between 1.5°K and 4.2°K, and was arranged so that infrared radiation from an outside source could fall on the orifice of the bolometer.

Between the infrared source and the cryostat housing the bolometer, a chopping disk was inserted. By having a two-speed motor and interchangable chopping disks of various aperture dimensions it could be arranged for the incident radiation on the bolometer to be a square wave of equal on and off periods and having frequencies of 130, 244, 272 and 512 cps.

The output from the bolometer was fed into the same low-noise narrow-band amplifying system and recorder as described in Section 3: and illustrated diagramatically in Fig. 1. The biasing current to the bolometer was fed from a small d-c source at room temperature, as shown also in Fig. 1.

(c) The measurements of the thermal conductance of the bolometer to its surroundings.

The thermal conductance, G, of the bolometer to its surroundings is defined by:

$$G \cdot \Delta T = P$$

where ΔT is the temperature difference between the bolometer and its

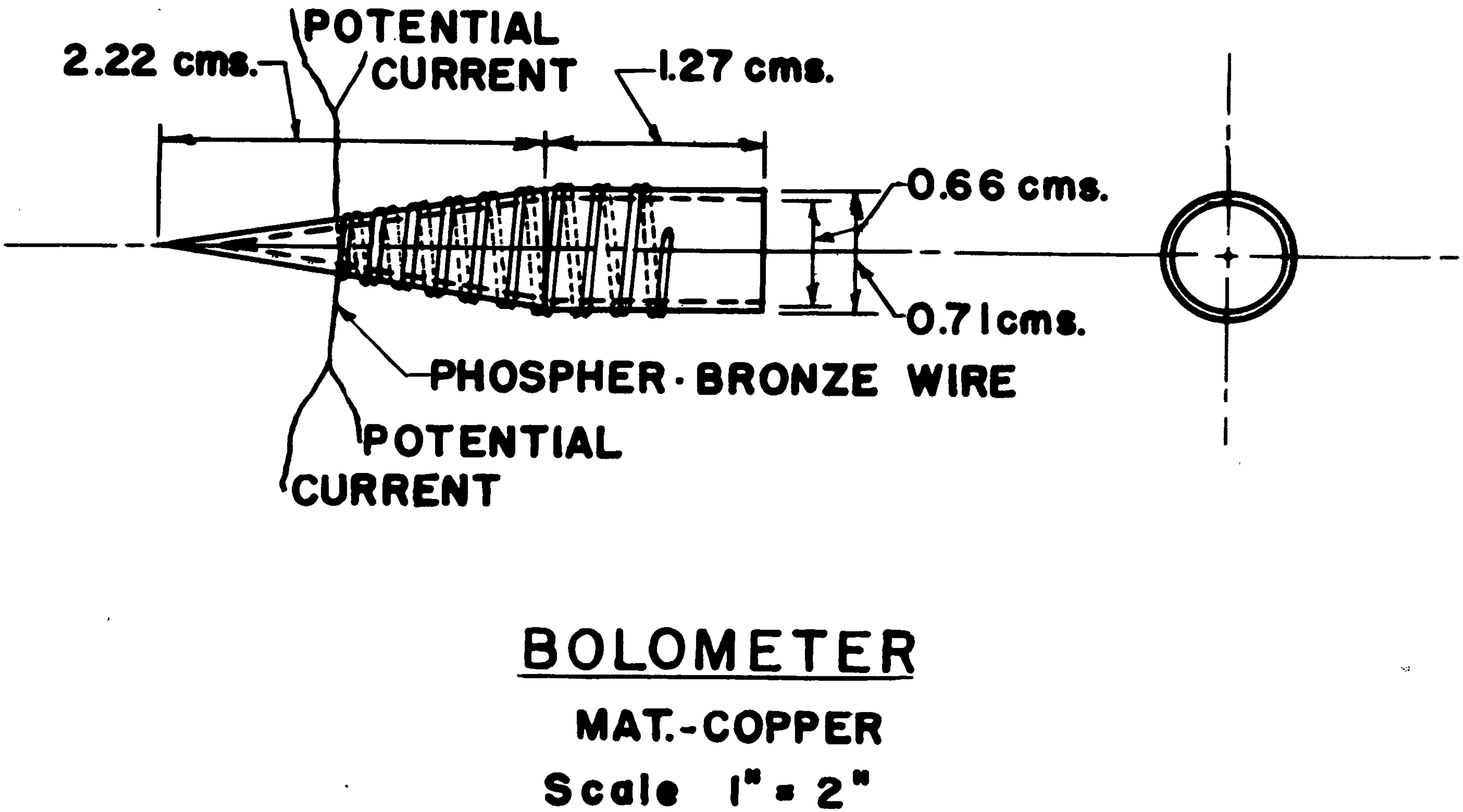

FIGURE 7. Diagram of bolometer element

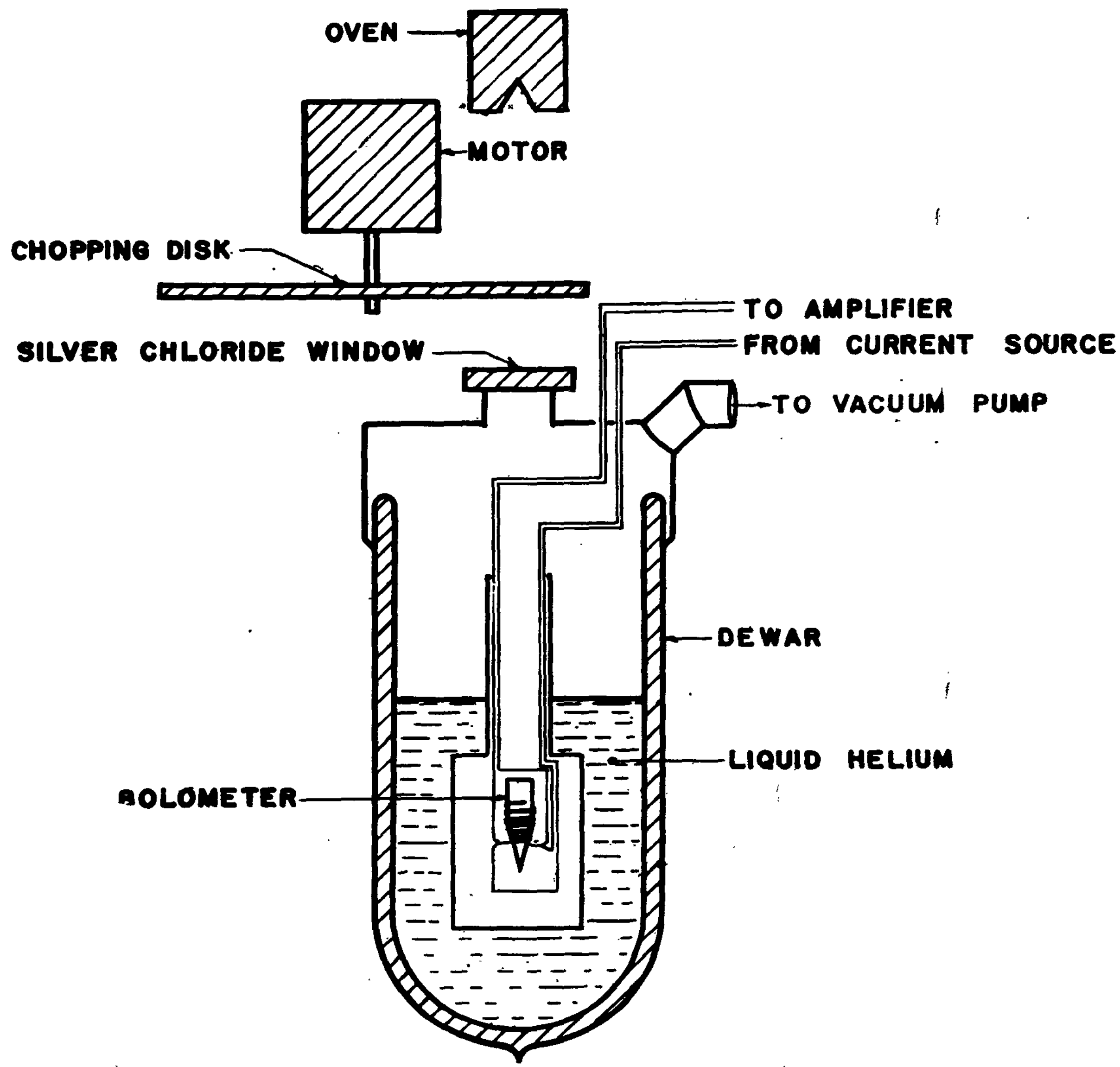

FIGURE 8. Schematic diagram of bolometer and cryostat mounting.

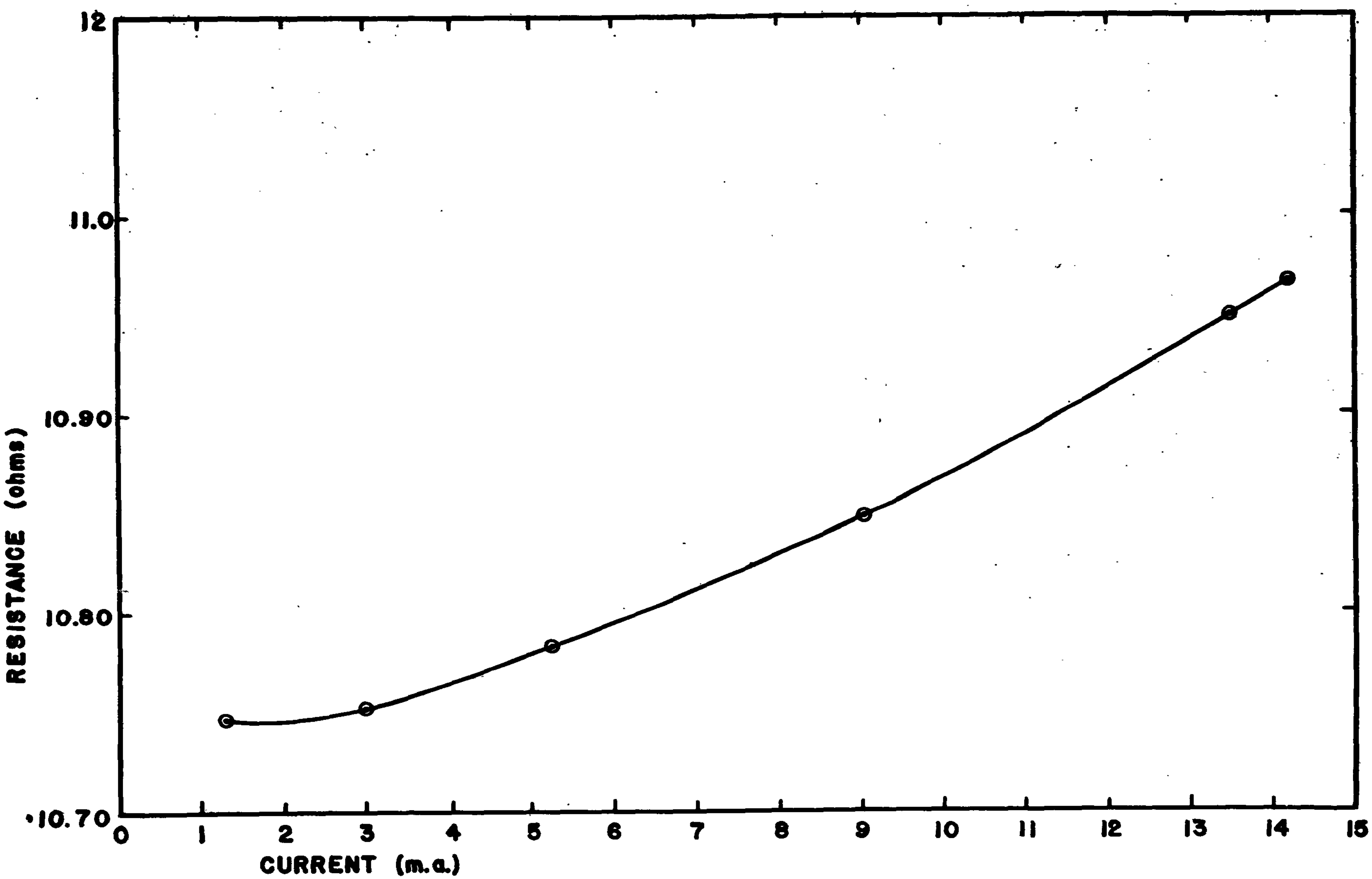

FIGURE 9. Plot of resistance, R, of bolometer element as a function of the d-c biasing current, i.

surroundings and P is the heat flow resulting from the temperature difference, ΔT.

The value of G for the bolometer described above was determined experimentally as follows: the temperature of the surroundings to the bolometer were kept constant by maintaining the liquid helium bath around it (see Fig. 8) boiling at constant vapor pressure; then measurements were made of the potential difference across the bolometer element for various d-c currents through it. A plot of a typical measurement is given in Fig. 9 in which the value of the resistance, R, of the phosphor-bronze wire computed from the measurements is plotted against the d-c biasing current, i. Since R is a known function of the temperature, T, the values of ΔT can also be obtained from the graph of Fig. 9 and these are shown plotted against the biasing power, P, in Fig. 10. It will be seen from the curve of ΔT versus P of Fig. 10 that there is an approximately linear relation between them, from which the value of G may be computed. The values of G obtained in this way at various temperatures (i.e. at various pressures of the helium vapor surrounding the bolometer) are given in Table II. It is to be noticed that whereas the pressure of the vapor surrounding the bolometer was changed by a factor of approximately three, the value of the thermal conductance, G, was not altered by more than 27 percent.

The values of g, i.e. the thermal conductance per unit area, given in Table II are to be compared with those measured by Kapitza [12] for copper surfaces immersed directly in liquid helium II of about $g = 0.4$ watts/deg-cm^2 at about 2°K. This figure obtained by Kapitza is more than 500 times greater than our measurements for surfaces immersed only in helium vapor at comparable temperatures; and the marked difference is no doubt attributable to the superfluid characteristics of helium II. It would be of interest to have similar measurements of the thermal conductance of surfaces to liquid helium I and it is hoped that we may be able to carry out such work in the future. It is to be expected that little difference in g values would result between those for surfaces immersed in liquid helium I and those for surfaces immersed in helium vapor at the same temperatures.

(d) The measurements of time constants of the bolometer.

The time constant was measured during two different helium runs and at different vapor pressures in order to ensure reproducibility.

12. P.L. Kapitza, Jour. Phys. USSR. 4, 181 (1951).

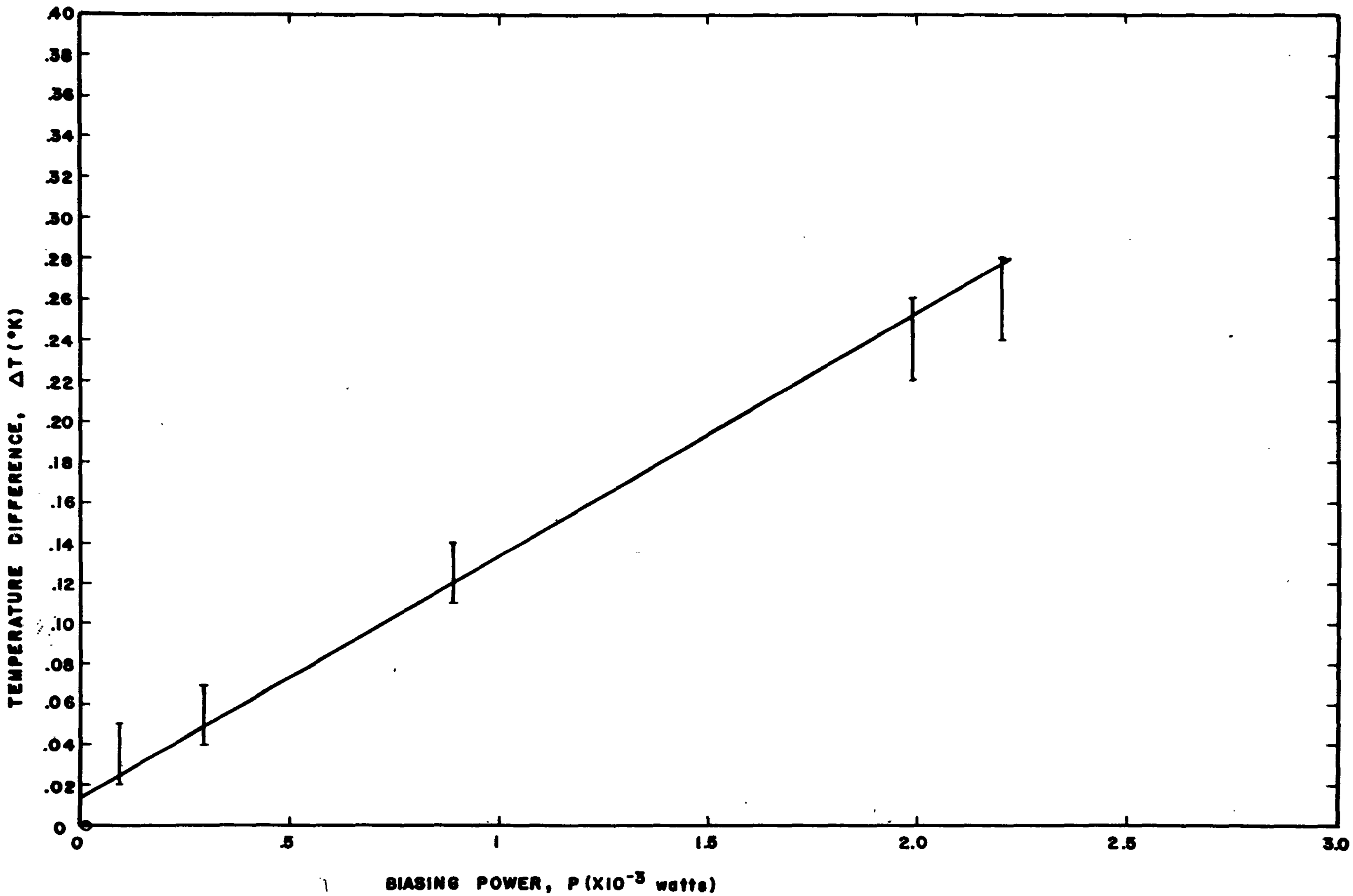

FIGURE 10. Plot of temperature difference, T, between bolometer and its surroundings as a function of the d-c power, P, put into the bolometer.

TABLE II.

Data on Thermal Conductances G and g *

Temp. ^oK	Vapor press. cm Hg	G. watts/deg	g. watts/deg-cm^2
2.31	5.14	7.25×10^{-3}	6.97×10^{-4}
2.52	8.04	8.35×10^{-3}	8.03×10^{-4}
2.78	12.94	10×10^{-3}	9.6×10^{-4}

* g is the thermal conductance per square cm of surface area and is obtained by dividing the value of G by the total surface area of the bolometer. (10.4 cm^2).

The measurements consisted in recording the bolometer response to fixed intensity of radiation for different chopping frequencies. The d-c biasing current was also held constant. The frequencies used are given in subsection 4 (b) above. After these measurements were made, the gain of the amplifier system, at the same gain setting, was measured at the different frequencies and this measurement was used to normalize the observed responses to constant gain. A plot of the reciprocal of the corrected recorder reading ($1/\theta$) versus the square of the chopping frequency, f^2, of the incident radiation for a typical run is given in Fig. 11. The plot is approximately linear and its intercept on the (negative) f^2 axis determines the time constant of the bolometer.

Since

$$\frac{1}{\theta} \propto \frac{1}{\Delta V^2} \propto \frac{1}{W} (G^2 + \omega^2 C^2)$$

where ΔV is the rms voltage across the bolometer due to the signal, W is the power of the incident radiation, ω the angular chopping frequency and C the thermal capacity of the bolometer, then the time

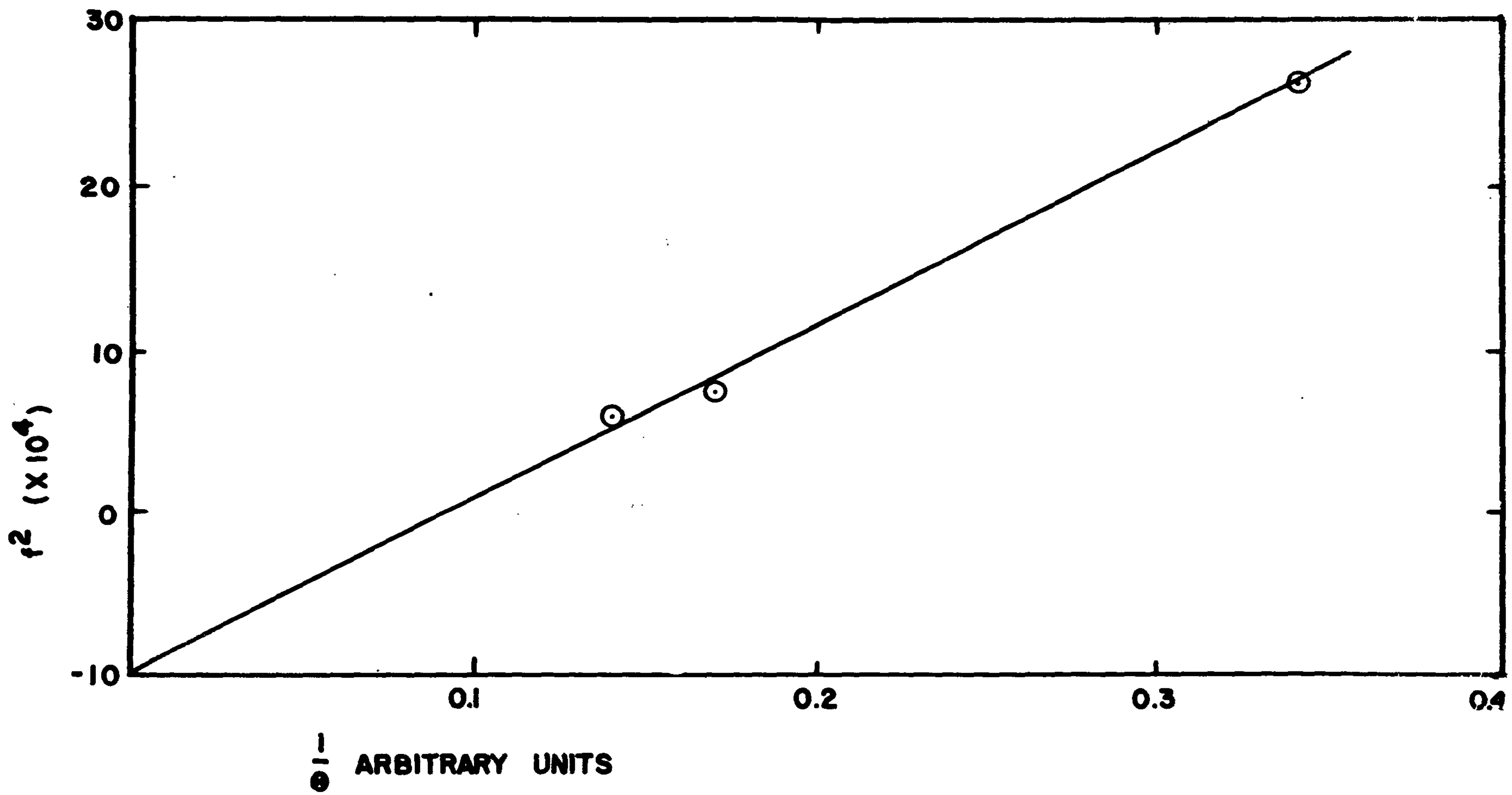

FIGURE 11. Plot of the reciprocal of the recorder reading, 1/Θ, against the square of the chopping frequency, f^2, for constant signal input power and constant gain.

constant, τ, of the bolometer (given by $\tau = 2\pi C/G$) will be obtained from:

$$\frac{1}{\theta} \propto \left(\frac{\omega^2}{4\pi^2} + \frac{1}{\tau^2} \right) \propto \left(f^2 + \frac{1}{\tau^2} \right)$$

i.e. from the intercept on the f^2 axis ($f^2 = \omega^2/4\pi^2$) of the $1/\theta$ versus f^2 plot.

Separate determinations of τ made in this way are presented in Table III, and yield a mean value of about 4×10^{-3} second.

TABLE III

Data on Time Constant Measurements.

Date	Temp. °K	τ (observed) sec.
8-8-52	2.99	3.1×10^{-3}
8-14-52	2.78	4.6×10^{-3}

It is of interest to note that when the liquid helium bath was taken below 2.2°K, i.e, into the region of liquid helium II, all signal response disappeared, presumably due to the high heat conductivity and superfluidity of the helium film phenomenon.

The observed values of τ of about 4×10^{-3} second were in agreement with what would be expected. The heat capacity of the bolometer can be roughly estimated from previous measurements on the specific heat of copper [13] in the helium temperature range. For the 1.31 g of copper in the bolometer, the heat capacity C at

and insulating varnish is assumed to be negligible compared with the mass of the copper. The time constant, τ, therefore is computed to be:

$$\tau = \frac{2\pi C}{G} = \frac{2\pi \times 1.6 \times 10^{-5}}{10^{-2}} \approx 10 \times 10^{-3} \text{ second,}$$

since the value of G has been previously measured (see Table II). This computed value of τ is in fair agreement with the observed value.

The reasons for such relatively small time constants, τ, are twofold, namely: (a) at the low temperatures employed, the specific heat of the bolometer materials are small, e.g. for copper the ratio of the specific heat C_v at 300°K to C_v at 2°K is 13,500:1, and consequently, relatively large masses may be employed and yet small heat capacities obtained; (b) by immersing the bolometer in helium vapor at from 5 cm Hg pressure to 15 cm Hg, the thermal conductance is large. This, however, is a drawback from the point of view of sensitivity.

(e) General Conclusions

It is not possible to quote a minimum detectable power for the bolometer for signal equal to noise from the preliminary experiments reported above. This is due to the following facts. First, we have not so far proceeded to calibrate the radiation from the source with sufficient accuracy, nor to assess the "blackness" of the bolometer. Secondly, we suffered spurious background noise from the motor operating the chopping dish, which did not allow an accurate assessment of the true thermal noise. This problem of picking noise is now being investigated. The calculated value for the power absorbed, W_{min}, in the bolometer such as to make the signal equal to the noise power is:

$$(W_{min})^2 = \frac{4K\, T_{eff.}\, \Delta f}{\alpha^2 p}\, G^2(1 + f^2\tau^2)$$

where α is the temperature coefficient of resistance of the bolometer element, P the d-c power dissipated, and where the other

symbols have their previously stated significance. Putting in the values of the parameters as used in a typical experimental observation we have : $T_{eff} = 10^oK$ (cf. subsection 4(c) in which it is shown that, due to amplifier noise, equivalent temperatures below about 10^oK are not readily observable; cf. also Fig. 2), f = 244, $\Delta f = 2.5$, $P = 4 \times 10^{-3}$ watts, and we get for our bolometer:

$$W_{min} \approx 1 \times 10^{-10} \text{ watts.}$$

Since in practice the heat capacity C of the bolometer could very easily be reduced considerably, perhaps even by a factor of 100 or more, it would also be possible then to reduce G in order to maintain the same time constant. This would result in much lower values of W_{min} than that quoted above, lower perhaps by a factor of 100. W_{min} can also be reduced by operating at a lower temperature, since α, the temperature coefficient of resistance increased with decreasing temperature. As previously stated, no attempt was made in the initial construction of this preliminary bolometer to optimize the conditions of design at construction. It is considered, therefore, that further experiments would be of value and interest.

5. Summary of Conclusions obtained; Notes for desirable future Action

No evidence of current noise, greater than 4.5 db above Johnson noise power, was observed in a resistor of leaded phosphor-bronze in the partially superconductive state at 2.2^oK where the temperature coefficient of resistance was 0.17 deg $^{-1}$. The measurements include a frequency range of from 200 to 4000 cps.

A non-optimized phosphor-bronze bolometer, suitable for millimeter wave or infrared detection, was constructed and tested. The time constant was measured and found to be 4×10^{-3} second. Measurements of its minimum detectable absorbed power, W_{min}, were masked by spurious "pickup" noise from the chopper motor. A calculated value for W_{min}, calculated from the measured thermal conductance, etc., of the bolometer, and the noise factor of the amplifier system, was 1×10^{-10} watts at about 250 cps.

The experiments indicate that this figure could be improved upon, perhaps by two orders of magnitude, by optimizing the design, and yet the small time constant of 4×10^{-3} second could be maintained.

Further experiments on this are desirable and are being planned.

Considerable current noise was observed in a tantalum wire when it was maintained in the intermediate superconducting state at

4.2^oK by means of a small magnetic field. The current noise power was porportional to the square of the d-c biasing current, i^2, and appeared to be largely independent of frequency up to 5000 cps. The ratio $(n - 1)$ of the current noise power to the Johnson noise power was found to be :

$$(n - 1)/i^2 = 15 \ (\mathrm{ma})^{-2}.$$

It is considered possible that the observed current noise is due to temperature fluctuations in the tantalum wire rather than to mechanisms characteristic of the intermediate state in superconductors. If this is so, this is the first experiment reported indicating the existence of temperature fluctuations.

Further experiments are being prepared and must be carried out to determine without doubt the fundamental causes of this observed current noise in tantalum.

It is concluded that if the observed current noise is due to temperature fluctuations, then tantalum in the intermediate state will form a bolometer material par excellence. Suggestions for suitable bolometer construction are put forward.

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